Radiation Effects in M&NEMS

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Abstract: *Advances in materials and fabrication processes are enabling miniaturization of functions, including gyroscopes, accelerometers, sensors, relays, oscillators, and logic devices, using Micro & Nano-scale Electro Mechanical Systems (M&NEMS). This project seeks to advance the understanding radiation effects on the relevant properties of the constituent materials and structures, particularly advanced 2D materials, and the implications for space and military applications.*

Keywords: Micro and Nano-scale Electro Mechanical Systems, 2D Materials, Radiation Effects

Introduction

Mission reliability and survivability of next-generation space-borne systems depends critically upon a detailed understanding of the radiation response and reliability of the constituent devices when exposed to the relevant radiation environment. The dramatic reduction in size and power consumption offered by micro- and nano-scale electromechanical systems (M&NEMS) offer compelling advantages for adoption in space and military systems. M&NEMS may be employed for a variety of sensor and actuation applications, oscillators, and have potential to be incorporated as high-reliability solid-state (logic) switches. The operating principles of many of these devices may provide inherent tolerance to single-event transient radiation effects (SEE).

While there has been considerable study of radiation effects on some of the common materials (single and poly crystalline silicon, and SiO_2), the study in the context of MEMS has been more limited, and mainly experimental. Reference [1] provides an excellent comprehensive summary of the published work on radiation effects in MEMS.. The general indication is that depending on the operating principal, MEMS can be sensitive to TID (charging of insulators) and to displacement damage at very high exposure doses.

Recently, fabrication process, namely the ability to create nano-scale structures, options for fabrication of native-oxide-free structures [3], and the introduction of new materials, have expanded the opportunities for M&NEMS, and the considerations for radiation effects. DTRA has recently initiated multiple projects in the study of various aspects and configurations of M&NEMS, of which this project is one. This specific project seeks to advance the understanding of the effect of radiation on the relevant electro-mechanical properties of the constituent materials and structures, focusing on 2D materials and CNTS, and the implications for space and military applications.

The key question for this work is: *How does radiation damage to constituent materials impact the mechanical and electrical basis of operation of M&NEM structures?* In particular, cumulative damage by non-ionizing energy loss can, in principle, alter the mechanical properties of structures such as cantilever's and 2D membranes, and trapped charge in insulators can impact electrical operating conditions. Presently, the extent to which such effects impact the operation of advanced M&NEM devices is unclear. This particular project combines expertise and experience in materials science, M&NEMS, and radiation effects of the University of California at Berkeley, Sandia National Laboratories, and Vanderbilt University to conduct a systematic study of the impact of relevant radiation types on the key operating properties of novel M&NEM structures, and to capture observed effects in finite element models.

2D NEMS

Two-dimensional atomic crystals (2DACs) including graphene, monolayer boron nitride (BN) and monolayer molybdenum disulfide (MoS_2), are promising for NEMS applications. 2DACs can sustain very large strains, 30% for graphene, 18% for MoS_2, without breaking due to low defect densities, crystalline character, and atomic thicknesses. This facilitates high-frequency operation. High electrical and thermal conductivities of 2DACs allow electrical actuation and readout of NEMs devices, and the atomic thickness leads to very low volume for interaction with radiation. However, the response of micromechanical properties to radiation damage is virtually unstudied.

Vanderbilt researchers have developed an experimental platform, single-layer graphene or MoS_2 NEM resonators

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with electrical actuation and read-out, suitable for measurement of mechanical properties (Young's modulus, breaking strength) of 2DACs to electron and ion irradiation (Fig. 1). Mechanical oscillations of suspended 2DACs are actuated by applying an AC voltage between the 2DACs and the underlying a gate electrode. The amplitude of the mechanical oscillations is obtained electrically by measuring transconductance. When graphene is at resonance, ~ 10 MHz - 500 MHz, we detect a peak in electrical conductivity. By analyzing changes of the resonant frequency as a function of applied forces, we extract the built-in strain, Young's modulus, and the thermal expansion coefficient. Mechanical breaking strength of 2DACs can be determined by increasing the externally applied gate voltage. Since the mechanical parameters are determined electrically, the test structure can be integrated with radiation sources to elucidate changes in mechanical properties as a function of radiation exposure.

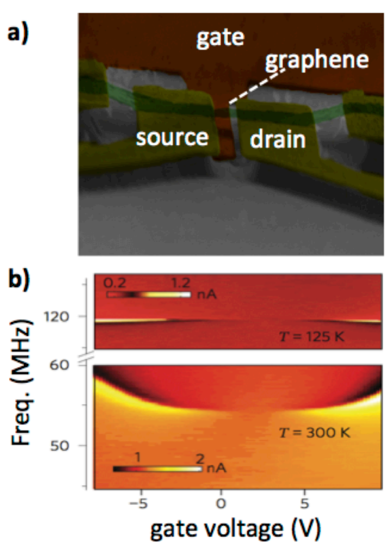

Figure 1. Probing mechanical properties of 2D materials using NEMs resonators. a) Electron microscopy image of a suspended graphene resonator. b) Changes of a resonant frequency of a graphene NEMs resonator vs. gate voltage. From the Bolotin group.

Suspended 2DAC materials also have the potential as a digital switch, for example as the graphene structure illustrated in Figure 2. Here, suspended graphene is actuated by an external voltage applied between graphene and underlying electrode. Modeling suggests that a voltage >10V causes the graphene to touch the electrode, allowing current flow in the graphene-electrode circuit. Among the advantages of this device design are very high on/off ratio and low on resistance. Moreover, high Young's modulus of graphene and the possibility of applying mechanical strain should allow these NEMs devices to operate at very high frequencies up to ~1GHz. Figure 3 shown a 2D cantilever with an option for a suspended silicon mass. We will study the effects of radiation on electrical conductivity, operational frequency, and failure modes.

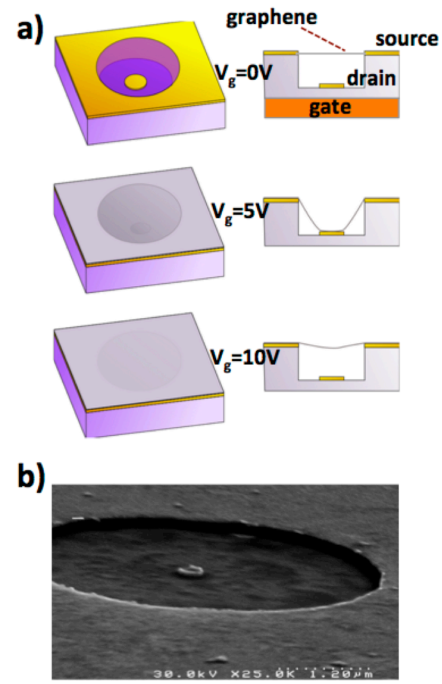

Figure. 2 Proposed design of a NEMs-based switch. a) Device operation. b) Electron microscopy image of a test device. From the Bolotin group.

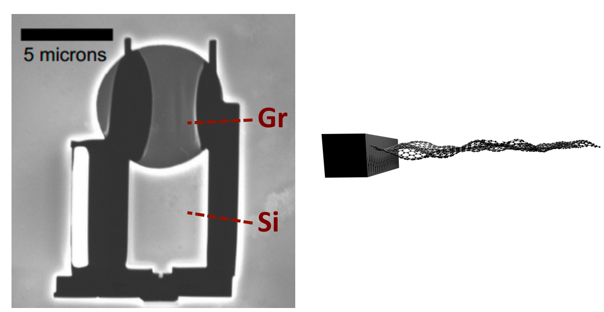

Figure. 3 Proposed design of a NEMs-based switch. a) Device operation. b) Electron microscopy image of a test device. From the Bolotin group.

CNT NEMS

The atomic perfection afforded by carbon nanotubes (CNTs) play a key role in NEMS applications. For example, the nested concentric cylinders of multiwall CNTs have been used to create rotational bearings for electrostatically-driven nanomotors (Figure 4), electrical rheostats, tunable electromechanical oscillators, and tunable thermal links. Cantilevered carbon nanotubes have also been used to create mechanical radio receivers and transmitters, and mass/chemical sensors with single-atom mass resolution at room temperature. Suspended graphene membranes driven electrostatically form high efficiency sound transducers operating in the audio to ultrasonic regime. Little is known about the radiation effects in such configurations. Indeed, in some cases radiation-induced changes in the NEMS structure may have beneficial effects (such as for activation of chemical reactivity in nanotube-based chemical sensors, or alteration of vibration of suspended graphene diaphragms where optimal mass/strength ratios may be achieved). In preliminary experiments by one of the PIs (Zettl), the effects of 100keV electron irradiation on the frictional properties of telescoping multiwall nanotubes (Figure 4) was investigated. It was found that, for mild irradiation times, hysteresis in force-displacement curves resulted, indicative of enhanced dissipation. Remarkably, such hysteresis was easily eliminated by continued cycling of the device; the irradiation-induced defects were there by apparently "annealed out".

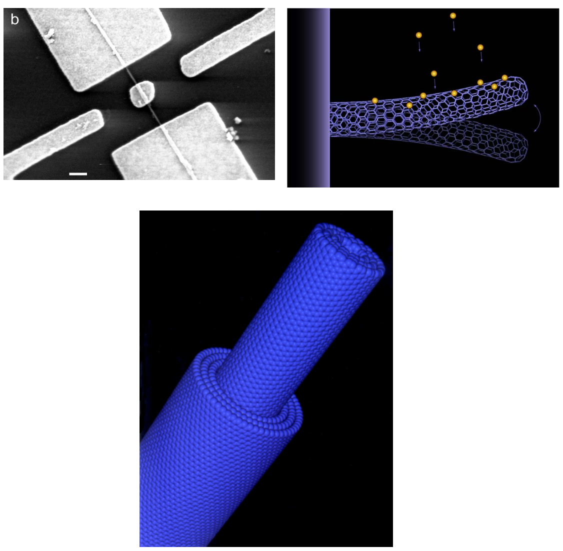

Figure 4. Top left: SEM image of fabricated nanomotor; Top right: Nanotube radio re-configured as atomic-resolution mass sensor; Bottom: Telescopically extended nanotube: The smoothest bearing? From the Zettl group.

This project will investigate the detailed influences of different radiation types on the evolution and operation of carbon-based NEMS bearings (linear and rotational) and oscillators. Some of the tests can be performed in-situ, where the device is operated or otherwise characterized (mechanically, thermally, electrically) while being irradiated, while others will necessitate a multi-step process of fabrication, testing, irradiation, testing, etc. Questions of critical importance that this project will address 1) how robust are CNT-based NEMS structures to irradiation effects in terms of enhanced dissipation (friction) or thermal/electrical performance degradation? 2) are radiation-generated defects annealed out by mechanical action or thermal (current) annealing; or do BN coatings change the radiation response? and 3) are there performance enhancements due to intentional irradiation?

Radiation Effects Characterization Considerations

The fundamental mechanisms of interaction of radiation with the constituent materials are the same for M&NEMS as for electronic devices (transistors). However, the manifestation and relative sensitivity to different types of radiation effects may differ, and depend on the operating principle of a given M&NEMS. For example, suspended structures with a native oxide coating may experience surface charge effects vs. transistor gates, which have adjacent materials on both sides. In addition, M&MEMS may be very sensitive to other environmental parameters, for example temperature and pressure. It is often desirable to operate M&NEMS oscillators under vacuum and at reduced temperatures. This introduces considerations for test setups (esp. for in situ characterization) as well as for interpretation of measured results, e.g. delineating effects of possible pressure and temperature changes from the impact of the radiation, and/or monitoring and controlling these other variables sufficiently. For M&NEMS, modification of mechanical properties is of great interest (in addition to electrical properties); this adds some complication for in-situ characterization. Finally, radiation effects on 2D and CNT NEM structures are relatively unexplored. To address the unique considerations for NEMS, this project is exploring hardware development to use in conjunction with the ARACOR 10 keV x-ray irradiator and Pelletron accelerator at Vanderbilt University.

In addition to the aforementioned experimental considerations specific to M&NEMS, this project will pursue two unique approaches. The first is the use of conventional silicon-based MEMS as a platform to manipulate and characterize 2D materials. Sandia National Laboratories has extensive experience and capabilities in the fabrication of MEMS (www.sandia.gov/mstc/mems/). The approach is to use those and integrate 2D materials. An example is shown in Figure 5 where the geometry will be configured to apply axial, bending or torsion strain to 2D material. The structures will be forced and sensed electrostatically and can be designed to test isotropic vs. orthotropic behavior.

The second characterization approach is the use of the TEAM 1.0 microscope at the National Center for Electron Microscopy (LBNL). This allows in-situ characterization of electron damage in 2D materials. Figure 6 shows microscope images of defects in bilayer h-BN, and the evolution of a torn graphene edge under the influence of the electron beam. The Zettle group has also developed capabilities for in-situ manipulation and characterization of nano-structures, enabling characterization while irradiating and/or joule heating a structure. The platform to probe mechanical properties of 2D materials inside a TEM is shown in Figure 7. Here a calibrated AFM tip is used to controllably buckle a CNT.

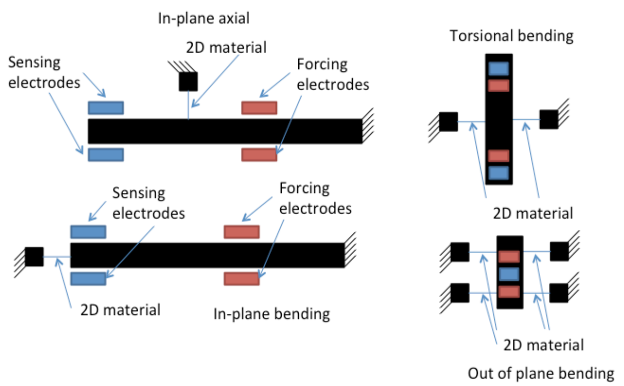

Figure 5. Proposed approach to combine single crystal silicon MEMS (Sandia) fab capabilities and form supporting structure for 2D materials (VU).

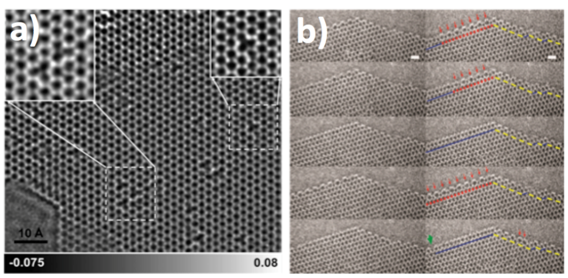

Figure 6. TEAM I microscope images showing a) defects in bilayer h-BN, and b) the evolution of a torn graphene edge under the influence of the electron beam. From the Zettl group.

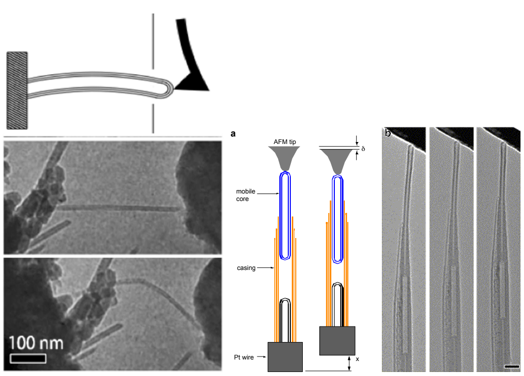

Figure 7. Left: A calibrated AFM tip is used to controllably buckle a CNT; Right: STM and AFM inside HRTEM for in-situ mechanical measurements. From the Zettl group.

Modeling

In addition to experimental studies, modeling will be applied to provide insight into the radiation effects mechanisms. Figure 8 shows examples of modeling of 2D NEM structures. The effect of radiation-induced parametric changes, for example Young's Modulus, will be used in models to predict the impact od performance of M&NEM devices.

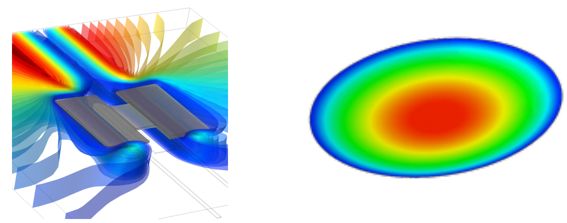

Figure 8. Left: electric field distribution surrounding a suspended membrane; Right strain in a flexed 2D membrane. From the Bolotin group.

Summary

The dramatic reduction in size and power consumption offered by micro- and nano-scale electromechanical systems (M&NEMS) offer compelling advantages for adoption in space and military systems. M&NEMS may be employed for a variety of sensor and actuation applications, oscillators, and have potential to be incorporated as high-reliability solid-state (logic) switches. New nano-scale structures, namely 2D materials and CNTs, offer tremendous potential for NEMS applications. This specific project seeks to advance the understanding of the effect of radiation on the relevant electro-mechanical properties of the constituent materials and structures, focusing on 2D materials and CNTS, and the implications for space and military applications.

Acknowledgements

The project depicted is sponsored by the Department of the Defense, Defense Threat Reduction Agency Grant # HDTRA1-15-1-0036. The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred.

References

[1] H. R. Shea, "Effects of Radiation on MEMS", Reliability, Packaging, Testing, and Characterization of MEMS/MOEMS and Nanodevices X, ,ed. by Sonia Garcia-Blanco, Rajeshuni Ramesham, Proc. of SPIE Vol. 7928, 79280E, 2011, doi: 10.1117/12.876968